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# A NOTE ON SERRIN'S OVERDETERMINED PROBLEM

GIULIO CIRAOLO AND ROLANDO MAGNANINI

ABSTRACT. We consider the solution of the torsion problem

$$-\Delta u = 1 \quad \text{in } \Omega, \quad u = 0 \quad \text{on } \partial\Omega.$$

Serrin's celebrated symmetry theorem states that, if the normal derivative  $u_\nu$  is constant on  $\partial\Omega$ , then  $\Omega$  must be a ball. In [6], it has been conjectured that Serrin's theorem may be obtained *by stability* in the following way: first, for the solution  $u$  of the torsion problem prove the estimate

$$r_e - r_i \leq C_t \left( \max_{\Gamma_t} u - \min_{\Gamma_t} u \right)$$

for some constant  $C_t$  depending on  $t$ , where  $r_e$  and  $r_i$  are the radii of an annulus containing  $\partial\Omega$  and  $\Gamma_t$  is a surface parallel to  $\partial\Omega$  at distance  $t$  and sufficiently close to  $\partial\Omega$ ; secondly, if in addition  $u_\nu$  is constant on  $\partial\Omega$ , show that

$$\max_{\Gamma_t} u - \min_{\Gamma_t} u = o(C_t) \quad \text{as } t \rightarrow 0^+.$$

The estimate constructed in [6] is not sharp enough to achieve this goal. In this paper, we analyse a simple case study and show that the scheme is successful if the admissible domains  $\Omega$  are ellipses.

## 1. INTRODUCTION

Let  $\Omega$  be a bounded domain in  $\mathbb{R}^N$  and let  $u$  be the solution of the torsion problem

$$(1.1) \quad -\Delta u = 1 \quad \text{in } \Omega, \quad u = 0 \quad \text{on } \partial\Omega.$$

Serrin's celebrated symmetry theorem [10] states that, if there exists a solution of (1.1) whose (exterior) normal derivative  $u_\nu$  is constant on  $\partial\Omega$ , that is such that

$$(1.2) \quad u_\nu = c \quad \text{on } \partial\Omega,$$

then  $\Omega$  is a ball and  $u$  is radially symmetric.

As is well-known, the proof of Serrin makes use of the *method of moving planes* (see [10, ?]), a refinement of Alexandrov's reflection principle [2].

The aim of this note is to probe the feasibility of a new proof of Serrin's symmetry theorem based on a comparison with another overdetermined problem for (1.1). In fact, it has been noticed that, under certain sufficient conditions on  $\partial\Omega$ , if the solution of (1.1) is constant on a surface *parallel* to  $\partial\Omega$ , that is, if for some small  $t > 0$

$$(1.3) \quad u = k \quad \text{on } \Gamma_t, \quad \text{where } \Gamma_t = \{x \in \Omega : \text{dist}(x, \partial\Omega) = t\},$$

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then  $\Omega$  must be a ball (see [8, 9, 6] and [11]).

Condition (1.3) was first studied in [8] (see also [9] and [5] for further developments), motivated by an investigation on *time-invariant level surfaces* of a nonlinear non-degenerate *fast diffusion* equation (tailored upon the heat equation), and was used to extend to nonlinear equations the symmetry results obtained in [7] for the heat equation. The proof still hinges on the method of moving planes, that can be applied in a much simplified manner, since the overdetermination in (1.3) takes place inside  $\Omega$ . Under slightly different assumptions and by a different proof — still based on the method of moving planes — a similar result was obtained in [11] independently.

The evident similarity between the two problems arouses a natural question: *is condition (1.3) weaker or stronger than (1.2)?*

As pointed out in [6], (1.3) seems to be weaker than (1.2), as explained by the following two observations: (i) as (1.3) does not imply (1.2), the latter can be seen as the limit of a sequence of conditions of type (1.3) with  $k = k_n$  and  $t = t_n$  and  $k_n$  and  $t_n$  vanishing as  $n \rightarrow \infty$ ; (ii) as (1.2) does not imply (1.3) either, if  $u$  satisfies (1.1)–(1.2), then the oscillation of  $u$  on a surface parallel to the boundary becomes smaller than usual, the closer the surface is to  $\partial\Omega$ . More precisely, if  $u \in C^1(\overline{\Omega})$ , by a Taylor expansion argument, it is easy to verify that

$$(1.4) \quad \max_{\Gamma_t} u - \min_{\Gamma_t} u = o(t) \quad \text{as } t \rightarrow 0$$

— that becomes a  $O(t^2)$  as  $t \rightarrow \infty$  when  $u \in C^2(\overline{\Omega})$ .

This remark suggests the possibility that Serrin's symmetry result may be obtained *by stability* in the following way: first, for the solution  $u$  of the torsion problem (1.1) prove the estimate

$$(1.5) \quad r_e - r_i \leq C_t \left( \max_{\Gamma_t} u - \min_{\Gamma_t} u \right)$$

for some constant  $C_t$  depending on  $t$ , where  $r_e$  and  $r_i$  are the radii of an annulus containing  $\partial\Omega$ ; secondly, if in addition  $u_\nu$  is constant on  $\partial\Omega$ , show that

$$\max_{\Gamma_t} u - \min_{\Gamma_t} u = o(C_t) \quad \text{as } t \rightarrow 0^+.$$

In the same spirit of (1.5), based on [1], in [6] we proved an estimate that quantifies the radial symmetry of  $\Omega$  in terms of the following quantity:

$$(1.6) \quad [u]_{\Gamma_t} = \sup_{\substack{z, w \in \Gamma_t \\ z \neq w}} \frac{|u(z) - u(w)|}{|z - w|}.$$

In fact, it was proved that there exist two constants  $\varepsilon, C_t > 0$  such that, if  $[u]_{\Gamma_t} \leq \varepsilon$ , then there are two concentric balls  $B_{r_i}$  and  $B_{r_e}$  such that

$$(1.7) \quad B_{r_i} \subset \Omega \subset B_{r_e} \quad \text{and} \quad r_e - r_i \leq C_t [u]_{\Gamma_t}.$$

The constant  $C_t$  only depends on  $t$ ,  $N$ , the regularity of  $\partial\Omega$  and the diameter of  $\Omega$ .

The calculations in [6] imply that  $C_t$  blows-up exponentially as  $t$  tends to 0, which is too fast for our purposes, since  $[u]_{\Gamma_t}$  cannot vanish faster than  $t^2$ , when (1.2) holds. The exponential dependence of  $C_t$  on  $t$  is due to the method of proof we employed, which is based on the idea of refining

the method of moving planes from a quantitative point of view. As that method is based on the maximum (or comparison) principle, its quantitative counterpart is based on *Harnack's inequality* and some quantitative versions of *Hopf's boundary lemma*. The exponential dependence of the constant involved in Harnack's inequality leads to that of  $C_t$ . Recent (unpublished) calculations, based on more refined versions of Harnack's inequality, show that the growth rate of  $C_t$  can be improved, but they are still inadequate to achieve our goal. Approaches to stability based on the ideas contained in [3] and [4] do not seem to work for problem (1.1)-(1.3).

In this note, we shall show that our scheme (i)-(ii) is successful, at least if the admissible domains are ellipses: in this case, the deviation from radial symmetry can be exactly computed in terms of the oscillation of  $u$  on  $\Gamma_t$ . We obtain (1.5) with  $C_t = O(t^{-1})$  as  $t \rightarrow 0^+$ ; thus, formula (1.4) yields the desired symmetry.<sup>1</sup>

## 2. SECTION 2

We begin by defining the three quantities that we shall exactly compute later on. Let  $\Gamma$  be a  $C^1$ -regular closed simple plane curve and let  $z(s)$ ,  $s \in [0, |\Gamma|)$  be its parameterization by arc-length. For a function  $u : \Gamma \rightarrow \mathbb{R}$ , we will consider the seminorms

$$(2.1) \quad |u|_\Gamma = \sup_{\substack{0 \leq s, s' \leq |\Gamma| \\ s \neq s'}} \frac{|u(z(s)) - u(z(s'))|}{\min(|s - s'|, |\Gamma| - |s - s'|)}, \quad [u]_\Gamma = \sup_{\substack{z, w \in \Gamma \\ z \neq w}} \frac{|u(z) - u(w)|}{|z - w|},$$

and the *oscillation*

$$(2.2) \quad \text{osc}_\Gamma u = \max_\Gamma u - \min_\Gamma u.$$

We now consider an ellipse

$$E = \{z = (x, y) \in \mathbb{R}^2 : \frac{x^2}{a^2} + \frac{y^2}{b^2} < 1\},$$

with semi-axes  $a$  and  $b$  normalized by  $a^{-2} + b^{-2} = 1$ , and let

$$(2.3) \quad \Gamma_t = \{z \in E : \text{dist}(z, \partial E) = t\}$$

be the curve parallel to  $\partial E$  at distance  $t$ ;  $\Gamma_t$  is still regular and simple if  $t$  is smaller than the minimal radius of curvature of  $\partial E$ , that is for

$$(2.4) \quad 0 \leq t < \frac{\min(a^3, b^3)}{2a^2b^2}.$$

The solution  $u$  of (1.1) is clearly given by

$$(2.5) \quad u(x, y) = 1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}.$$

**Lemma 2.1.** *Let  $u$  be given by (2.5) and let  $t$  satisfy (2.4). Then, we have:*

- (i)  $|u|_{\Gamma_t} = |a - b| \frac{a + b}{a^2 b^2} t$ ;
- (ii)  $[u]_{\Gamma_t} = |u|_{\Gamma_t}$ ;

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<sup>1</sup>Of course, in this very special case, there is a trivial proof of symmetry, but this is not the point.

$$(iii) \quad \text{osc}_{\Gamma_t} u = |a - b| \frac{a + b}{a^2 b^2} \left( \frac{2ab}{a + b} - t \right) t.$$

*Proof.* The standard parametrization of  $\partial E$  is

$$\gamma(\theta) = (a \cos \theta, b \sin \theta), \quad \theta \in [0, 2\pi];$$

thus,

$$\Gamma_t = \left\{ \gamma(\theta) - t J \frac{\gamma'(\theta)}{|\gamma'(\theta)|} : \theta \in [0, 2\pi) \right\},$$

where  $J$  is the rotation matrix

$$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},$$

so that the outward unit normal is

$$\nu(\theta) = J \frac{\gamma'(\theta)}{|\gamma'(\theta)|}.$$

(i) The mean value theorem then tells us that

$$(2.6) \quad \frac{|u(z(s)) - u(z(s'))|}{\min(|s - s'|, |\Gamma_t| - |s - s'|)} = |\langle Du(z(\sigma)), z'(\sigma) \rangle|,$$

for some  $\sigma \in [0, |\Gamma_t|]$ . Since  $\Gamma_t$  is parallel to  $\partial E$ , we have

$$z'(\sigma) = \frac{\gamma'(\theta(\sigma))}{|\gamma'(\theta(\sigma))|},$$

where  $\theta(\sigma)$  is such that

$$z(\sigma) = \gamma(\theta(\sigma)) - t \nu(\theta).$$

By (2.5), we have that

$$|\langle Du(z(\sigma)), z'(\sigma) \rangle| = 2 |\langle Az(\sigma), z'(\sigma) \rangle| \quad \text{with} \quad A = \begin{pmatrix} a^{-2} & 0 \\ 0 & b^{-2} \end{pmatrix},$$

and hence

$$|\langle Du(z(\sigma)), z'(\sigma) \rangle| = 2 \left| \frac{\langle A \gamma(\theta), \gamma'(\theta) \rangle}{|\gamma'(\theta)|} - t \frac{\langle A J \gamma'(\theta), \gamma'(\theta) \rangle}{|\gamma'(\theta)|^2} \right|,$$

with  $\theta = \theta(\sigma)$ .

Straightforward computations give:

$$\begin{aligned} \gamma'(\theta) &= (-a \sin \theta, b \cos \theta), \quad |\gamma'(\theta)| = \sqrt{a^2 \sin^2 \theta + b^2 \cos^2 \theta}, \\ \langle A \gamma(\theta), \gamma'(\theta) \rangle &= 0, \quad \langle A J \gamma'(\theta), \gamma'(\theta) \rangle = \frac{|a^2 - b^2|}{ab} \sin \theta \cos \theta. \end{aligned}$$

Therefore,

$$|\langle Du(z(\sigma)) \cdot z'(\sigma) \rangle| = \frac{|a^2 - b^2|}{ab} \frac{2 |\tan \theta|}{a^2 \tan^2 \theta + b^2} t;$$

this expression achieves its maximum if  $|\tan \theta| = b/a$ , that gives:

$$\max_{0 \leq \sigma \leq |\Gamma_t|} |\langle Du(z(\sigma)), z'(\sigma) \rangle| = |a^{-2} - b^{-2}| t.$$

From (2.6) we conclude.

(ii) By a symmetry argument, we can always assume that  $[u]_{\Gamma_t}$  is attained for points  $z$  and  $w$  (that may possibly coincide) in the first quadrant of the cartesian plane.

Now, suppose that the value  $[u]_{\Gamma_t}$  is attained for two points  $z, w \in \Gamma_t$  with  $z \neq w$ . Let  $s \rightarrow z(s) \in \Gamma_t$  be a parametrization by arclength of  $\Gamma_t$  such that  $z(0) = z$  and let  $\omega = z'(0)$  be the tangent unit vector to  $\Gamma_t$  at  $z$ . The function defined by

$$f(s) = \frac{u(z(s)) - u(w)}{|z(s) - w|}$$

has a relative maximum at  $s = 0$  and hence  $f'(0) = 0$ ; thus,

$$\frac{\langle Du(z), \omega \rangle}{|z - w|} = \frac{u(z) - u(w)}{|z - w|} \frac{\langle z - w, \omega \rangle}{|z - w|^2}.$$

Therefore, since  $\langle z - w, \omega \rangle \neq 0$ , we have that

$$[u]_{\Gamma_t} = \frac{\langle Du(z), \omega \rangle}{\langle z - w, \omega \rangle} |z - w|,$$

that gives a contradiction, since the right-hand side increases with  $z$  if the angle between  $z - w$  and  $\omega$  decreases.

As a consequence, we infer that

$$[u]_{\Gamma_t} = \lim_{n \rightarrow \infty} \frac{u(z_n) - u(w_n)}{|z_n - w_n|} \text{ where } z_n, w_n \in \Gamma_t \text{ and } |z_n - w_n| \rightarrow 0.$$

Thus, by compactness, we can find a point  $z \in \Gamma_t$  such that

$$[u]_{\Gamma_t} = \langle Du(z), \omega \rangle,$$

where  $\omega$  is the tangent unit vector to  $\Gamma_t$  at  $z$ .

It is clear now that  $[u]_{\Gamma_t} = |u|_{\Gamma_t}$ .

(iii) If (2.4) holds, the maximum and minimum of  $u$  on  $\Gamma_t$  are attained at the points on  $\Gamma_t$  whose projections on  $\partial E$  respectively maximize and minimize  $|Du|$  on  $\partial E$ . Thus, (iii) follows at once.

In fact, for a point  $z = \gamma(\theta) - t\nu(\theta)$  on  $\Gamma_t$ , calculations give that

$$\begin{aligned} u(z) &= 1 - \langle A\gamma(\theta), \gamma(\theta) \rangle + 2t \langle A\gamma(\theta), \nu(\theta) \rangle - t^2 \langle A\nu(\theta), \nu(\theta) \rangle = \\ &= 2t \langle A\gamma(\theta), \nu(\theta) \rangle - t^2 \langle A\nu(\theta), \nu(\theta) \rangle, \end{aligned}$$

where

$$\begin{aligned} \langle A\gamma(\theta), \nu(\theta) \rangle &= \frac{1}{ab} \sqrt{b^2 \cos^2 \theta + a^2 \sin^2 \theta}; \\ \langle A\nu(\theta), \nu(\theta) \rangle &= \frac{1}{a^2 b^2} \frac{b^4 \cos^2 \theta + a^4 \sin^2 \theta}{b^2 \cos^2 \theta + a^2 \sin^2 \theta}, \end{aligned}$$

so that, by the substitution  $\xi = \sqrt{b^2 \cos^2 \theta + a^2 \sin^2 \theta}$ , we obtain that

$$u(z) = \frac{2t}{ab} \xi + \frac{t^2}{\xi^2} - (a^{-2} + b^{-2}) t^2.$$

Since (2.4) holds, this function is respectively maximal or minimal when  $\xi = \min(a, b)$  or  $\max(a, b)$ .  $\square$

Therefore, for an ellipse  $E$ , [6][Theorem 1.1] can be stated as follows, together with two analogues.

**Theorem 2.2.** *Let  $u$  be the solution of (1.1) in an ellipse  $E$  of semi-axes  $a$  and  $b$ . Let  $\Gamma_t$  be the curve (2.3) parallel to  $\partial E$  at distance  $t$  satisfying (2.4).*

*Then, there are two concentric balls  $B_{r_i}$  and  $B_{r_e}$  such that  $B_{r_i} \subset E \subset B_{r_e}$  and*

$$r_e - r_i = \frac{1}{t} \frac{a^2 b^2}{a + b} |u|_{\Gamma_t}; \quad r_e - r_i = \frac{1}{t} \frac{a^2 b^2}{a + b} [u]_{\Gamma_t};$$

$$r_e - r_i = \frac{1}{t} \frac{a^2 b^2}{a + b} \operatorname{osc}_{\Gamma_t} u.$$

*Proof.* The largest ball contained in  $E$  and the smallest ball containing  $E$  are centered at the origin and have radii  $\min(a, b)$  and  $\max(a, b)$ , respectively; hence,  $r_e - r_i = |a - b|$  and the desired formulas follow from Lemma 2.1.  $\square$

Now, we turn to Serrin problem (1.1)-(1.2). The following lemma holds for quite general domains in general dimension .

**Lemma 2.3.** *Let  $\Omega \subset \mathbb{R}^N$  be a bounded domain with boundary of class  $C^2$  and let  $u \in C^1(\overline{\Omega}) \cap C^2(\Omega)$  be a solution of (1.1) satisfying (1.2).*

*Then*

$$\operatorname{osc}_{\Gamma_t} u = o(t) \quad \text{as } t \rightarrow 0^+.$$

*If, in addition,  $u \in C^2(\overline{\Omega})$ , then*

$$[u]_{\Gamma_t} \quad \text{and} \quad |u|_{\Gamma_t} = o(t) \quad \text{as } t \rightarrow 0^+.$$

*Proof.* Let  $z$  and  $z' \in \Gamma_t$  points at which  $u$  attains its maximum and minimum, respectively (for notational simplicity, we do not indicate their dependence on  $t$ ). If  $t$  is sufficiently small, they have unique projections, say  $\gamma$  and  $\gamma'$ , on  $\partial\Omega$ , so that we can write that  $z = \gamma - t\nu(\gamma)$  and  $z' = \gamma' - t\nu(\gamma')$ .

Since both  $u$  and  $u_\nu$  are constant on  $\partial\Omega$ , Taylor's formula gives:

$$u(z) - u(z') = \int_0^t [\langle Du(\gamma' - \tau\nu(\gamma')), \nu(\gamma') \rangle - \langle Du(\gamma - \tau\nu(\gamma)), \nu(\gamma) \rangle] d\tau.$$

By the (uniform) continuity of the first derivatives of  $u$  (and the normals), the right-hand side of the last identity is a  $o(t)$  as  $t \rightarrow 0^+$ .

We shall prove the second part of the theorem only for the semi-norm  $[u]_{\Gamma_t}$ , since that for  $|u|_{\Gamma_t}$  runs similarly.

Let  $s$  and  $s' \in [0, |\Gamma_t|]$  attain the first supremum in (2.1); we apply (2.6) and obtain that

$$\frac{|u(z(s)) - u(z(s'))|}{\min(|s - s'|, |\Gamma_t| - |s - s'|)} = |\langle Du(z(\sigma)), z'(\sigma) \rangle|,$$

for some  $\sigma \in [0, |\Gamma_t|]$ . Let  $\gamma \in \partial\Omega$  be the projection of the point  $z = z(\sigma)$  on  $\partial\Omega$ , that is  $z = \gamma - t\nu(\gamma)$ .

Since  $\partial\Omega$  and  $\Gamma_t$  are parallel, the tangent unit vector  $\tau(\gamma)$  to the curve  $\sigma \mapsto \gamma(\sigma) \in \partial\Omega$  at  $\gamma$  equals the tangent unit vector  $\tau(z)$  to the curve  $\sigma \mapsto z(\sigma) \in \Gamma_t$  at  $z$ ; the same occurs for the corresponding normal unit vectors  $\nu(\gamma)$  and  $\nu(z)$ .

It is clear that  $\langle Du(\gamma), \tau(\gamma) \rangle = 0$  and, since  $u \in C^2(\overline{\Omega})$ , by differentiating (1.2), we also have that  $\langle D^2u(\gamma)\nu(\gamma), \tau(\gamma) \rangle = 0$ ; thus, by Taylor's formula,

we obtain that

$$\langle Du(z(\sigma)), z'(\sigma) \rangle = \langle Du(\gamma), \tau(\gamma) \rangle - t \langle D^2 u(\gamma) \nu(\gamma), \tau(\gamma) \rangle + R(s, s', t) = R(s, s', t).$$

Since the second derivatives of  $u$  are uniformly continuous on  $\overline{\Omega}$ , we conclude that the remainder term  $R(s, s', t)$  is a  $o(t)$  as  $t \rightarrow 0^+$ .  $\square$

**Theorem 2.4.** *Let  $E$  be an ellipse of semi-axes  $a$  and  $b$  and assume that in  $E$  there exists a solution  $u$  of (1.1) satisfying (1.2).*

*Then  $a = b$ , that is  $E$  is a ball and  $u$  is radially symmetric.*

*Proof.* Theorem 2.2 and Lemma 2.3 in any case yield that

$$|a - b| = o(1) \quad \text{as } t \rightarrow 0^+,$$

which implies the assertion.  $\square$

## REFERENCES

- [1] A. Aftalion, J. Busca, W. Reichel, Approximate radial symmetry for overdetermined boundary value problems, *Adv. Diff. Eq.* 4 no. 6 (1999), 907–932.
- [2] A. D. Aleksandrov, Uniqueness theorems for surfaces in the large V, *Vestnik Leningrad Univ.* 13, no. 19 (1958), 5–8. (English translation: *Amer. Math. Soc. Translations*, Ser. 2, 21 (1962), 412–415.)
- [3] B. Brandolini, C. Nitsch, P. Salani, C. Trombetti, On the stability of the Serrin problem, *J. Diff. Equations* vol. 245, Issue 6 (2008), 1566–1583.
- [4] B. Brandolini, C. Nitsch, P. Salani, C. Trombetti, Stability of radial symmetry for a Monge-Ampère overdetermined problem, *Annali Mat. Pura e Appl.* (4) 188 no. 3 (2009), 445–453.
- [5] G. Ciraolo, R. Magnanini, S. Sakaguchi, Symmetry of solutions of elliptic and parabolic equations with a level surface parallel to the boundary. To appear in *J. Eur. Math. Soc. (JEMS)*. ArXiv: 1203.5295.
- [6] G. Ciraolo, R. Magnanini, S. Sakaguchi, Solutions of elliptic equations with a level surface parallel to the boundary: stability of the radial configuration. To appear in *J. Analyse Math.* arXiv:1307.1257.
- [7] R. Magnanini, S. Sakaguchi, Matzoh ball soup: heat conductors with a stationary isothermic surface, *Ann. of Math.* 156 (2002), 931–946.
- [8] R. Magnanini, S. Sakaguchi, Nonlinear diffusion with a bounded stationary level surface, *Ann. Inst. H. Poincaré Anal. Non Linéaire*, 27 (2010), pp. 937–952.
- [9] R. Magnanini, S. Sakaguchi, Matzoh ball soup revisited: the boundary regularity issue, *Math. Meth. Appl. Sci.* 36 (2013), 2023–2032.
- [10] J. Serrin, A symmetry problem in potential theory, *Arch. Rational Mech. Anal.* 43 (1971), 304–318.
- [11] H. Shahgholian, Diversifications of Serrin’s and related symmetry problems, *Comp. Var. Elliptic Eq.*, 57 (2012), 653–665.

DIPARTIMENTO DI MATEMATICA E INFORMATICA, UNIVERSITÀ DI PALERMO, VIA ARCHIRAFI 34, 90123, ITALY.

*E-mail address:* [g.ciraolo@math.unipa.it](mailto:g.ciraolo@math.unipa.it)

*URL:* <http://www.math.unipa.it/~g.ciraolo/>

DIPARTIMENTO DI MATEMATICA ED INFORMATICA “U. DINI”, UNIVERSITÀ DI FIRENZE, VIALE MORGAGNI 67/A, 50134 FIRENZE, ITALY.

*E-mail address:* [magnanin@math.unifi.it](mailto:magnanin@math.unifi.it)

*URL:* <http://web.math.unifi.it/users/magnanin>